

# **Developing Lead-Alloys Target and Coolant Technology for Advanced Nuclear Systems – U.S. Program Plan**

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## ***Introduction***

Lead-alloys (lead, lead-bismuth eutectic) technology is being developed for high-power spallation neutron target and nuclear coolant applications. This program plan takes into account the strategic goals of the Advanced Fuel Cycle Initiative (AFCI) and Generation IV Nuclear Energy Systems (Gen IV), and the phased R&D approach with technology and system selection decisions in 2007-2010 timeframe. It assesses the key technology gaps that need to be filled to reduce technical risks and support the program decisions, and outlines a 5-year development plan.

## ***AFCI and Gen IV Programmatic Goals***

The Gen IV Program aims to develop advanced nuclear energy systems that offer significant advances toward sustainability, economics, safety and reliability, proliferation resistance and physical protection, that are deployable by 2030 or earlier. Lead-alloys cooled fast reactors (LFR) are one of the options selected for further evaluation and development.

The AFCI Program aims to develop fuel cycle technologies that: (1) enable recovery of the energy value from commercial spent nuclear fuel; (2) reduce the toxicity of high-level nuclear waste bound for geologic disposal; (3) reduce the inventories of civilian plutonium in the U.S.; and (4) enable more effective use of the currently proposed geologic repository and reduce the cost of geologic disposal.

In AFCI Series II, the program will develop and demonstrate nuclear waste transmutation through advanced reactors (Gen IV FR) and accelerator-driven systems (ADS) by 2030. Gen IV LFRs and ADS with LBE spallation target and coolant are options under evaluation and development.

According to these strategic goals, both AFCI and Gen IV use a phased approach to R&D and option selection. Both programs will make technology and reactor concept selection around 2007-2010 timeframe.

LBE technology development has been supported by AFCI (including predecessors ATW and AAA Programs) for the past few years, and is now jointly supported by Gen IV LFR.



The programmatic goal of US lead-alloys coolant technology development is to perform viability studies, reduce technical risks and support the 2007-2010 programmatic selection decisions.

### ***Lead-Alloys Target and Coolant Technology Gap Analysis***

LBE nuclear coolant technology has been developed and deployed in the former Soviet Union's nuclear navy program. Lead-cooled BREST-300 and LBE-cooled SVBR75/100 are currently under development in Russia. This indicates that the viability of lead-alloys coolant technology has been confirmed.

However, the Russian technologies are not yet fully disclosed and verified. In any case, critical techniques, materials and performance data will need to be developed and validated in compliance to the Western quality assurance standards and regulatory requirements. In addition, the use of LBE in high-power spallation neutron targets for ADS presents material and technological challenges not encountered in critical reactor applications.

The international programs to develop lead-alloys technology for ADS and FR have identified key gaps between the current state of the technology and the readiness levels required for programmatic applications. The following areas are summarized from the AFCI, Gen IV and JNC's FBR feasibility studies:

- (1) Materials Compatibility and Corrosion, Coolant Chemistry – corrosion of structural materials by lead-alloys is uniformly regarded as the most critical problem. The common approaches to solving this are to combine coolant chemistry (oxygen concentration) control with surface treatment and/or special alloying. These approaches have been proven in laboratory experiments or are under development. However the corrosion data under relevant conditions (temperature, flow, and coolant chemistry) is still insufficient for design purposes.

Coolant chemistry control is inseparable from corrosion performance. Using active control of oxygen to mitigate steel corrosion and prevent coolant contamination is largely validated by thermodynamic studies and laboratory tests. The optimal oxygen levels, the reliable operation of oxygen control systems, including oxygen sensors, the corrosion kinetics and the efficacy under poor flow conditions (e.g. in stagnant volumes, and in natural convection cooled large systems) still need to be investigated.

The compatibility of fuels, cladding and coolant has not been studied. To support LFR and LBE ADS decisions, proof of compatibility based on phase diagram studies and experiments at normal operating temperatures and under accident conditions needs to be achieved.



For spallation target applications, the effects of spallation products on material corrosion resistance are not well understood.

The effects of radiation on materials, corrosion and coolant chemistry need to be investigated.

- (2) Heat Transfer and Thermal Hydraulics – the availability of data for lead-alloys is poor and scattered. There are experimental data and correlations for Na, Pb-17Li and other liquid metals. The applicability to liquid lead-alloys needs to be confirmed. Heat transfer properties in prototypic configurations (e.g. rods and annulus, target window etc) need to be obtained and verified.

It is likely that the heat transfer and thermal hydraulics performance of lead-alloys also depends on coolant chemistry, especially under off-normal and accident conditions. Such dependence and the range of uncertainty need to be investigated.

Lead-alloys possess the highest potential for natural convection cooling. This feature is used in many proposed system concepts to enhance safety and/or reduce reliance on pumps. Several key aspects, such as transients to steady states, flow distribution and stability, need experimental characterization.

- (3) Radioactive Products and Activated Contaminants – the alpha-active polonium produced from irradiated bismuth is widely recognized as a key radioactive hazard in lead-bismuth coolant. The effects of such radioactive products on operation and maintenance safety, and the need and means to extract them should be studied.

For targets, there are a number of spallation products, particularly mercury and polonium, can present significant safety problems. The large quantities of gases (hydrogen and helium) produced can have detrimental effects on materials and corrosion. Mitigation strategies and methods need to be developed.

- (4) Erosion, Erosion/Corrosion and Liquid Metal Embrittlement – these phenomena may be encountered under high flow velocity, highly turbulent flow in transition zones (flow expansion, contraction and turning), and depletion of oxygen. The boundaries for these damaging conditions need to be experimentally characterized.
- (5) In Service Inspection (ISI) Methods – liquid metals present special challenges for ISI. Reliable flow measurement (especially velocity fields and pressure), interface monitoring (e.g. SCC, corrosion/precipitation), and impurity measurement need to be developed.
- (6) Safety, Decontamination and Decommission (D&D) – lead and lead oxides are chemical hazards that require special engineering and operation controls. The high density of lead-alloys also requires seismic consideration and changes to safety and



control system designs. The methodology of D&D needs to be developed before large lead-alloy-cooled systems can be designed and constructed.

To support AFCI and Gen IV LFR technology and concept selections, proof-of-principle R&D are needed for most of these areas to fill in the gaps. In the area of corrosion and coolant chemistry control, proof-of-performance for reference materials and coolant chemistry under out-of-pile conditions is needed. If the lead-alloys technology and LFR concept are selected, proof-of-performance R&D will commence in conjunction with design efforts. Some long-term proof-of-performance R&D (e.g. materials performance for long-life cores, radiation damages at high doses concurrent with other environmental effects etc) will have to be performed in demonstration units or under “test-and-licensing” conditions.

### ***Program Development Plan***

The transmutation engineering coolant materials effort will provide data and information to both the AFCI and the Generation IV Program to reduce technical risks associated with the selection of technology options. Existing and new facilities will be used in the next five years to perform corrosion and erosion, thermal hydraulic, thermodynamic, radiation environment effects and instrumentation tests, with the support of off-line development of sensors, control systems, measurement techniques, impurity and corrosion products removal techniques, and modeling. In addition, radiation hardened instruments adapted to high temperature coolant flows will be developed and tested.

The primary facility to be used is the DELTA Loop at LANL. It was designed and built to study materials and thermal hydraulics of lead and lead-alloy (lead-bismuth eutectic) systems. It is very versatile and sufficiently instrumented for multiple testing and development tasks identified as critical in the AFCI and Generation IV roadmaps. For the coolant materials, the objectives include defining corrosion mechanisms, providing solutions, and determining limits on thermodynamic and thermal-hydraulic parameters.

The DELTA Loop is a medium-scale forced circulation flow loop that can provide flow and temperature conditions prototypical of nuclear applications (reactors and high power spallation neutron targets), with coolant chemistry (oxygen) control. The processes of design, construction, shakedown testing, instrumentation, measurement and operation are integral to lead/lead-alloy liquid metal coolant technology development because the goal is to develop the technology to a level of maturity suitable for deployment with sufficient technical risk reduction. This task is supported by other essential R&D activities to achieve more systematic understanding of the various underpinnings of the lead-alloy coolant technology and materials.

The main portion of the DELTA Loop is a flow system consisting of a centrifugal pump (25 hp), 2 heat exchangers, a main heating zone (60 kW), oxygen sensors and control system, valves and piping network with trace heaters, insulation, temperature and flow measurement transducers and structural supports. It is capable of 58 gpm maximum flow



rate, over 2 m/s in test sections, and a temperature difference of over 100°C. The vertical configuration of the loop with the main heater at the bottom and the heat exchanger near the top allows for significant natural convection. The system is completely controlled through a LabView driven automated data acquisition and control (DAC) computer system, with a redundant safety system to prevent temperature and pressure deviation from the normal operating ranges.

New bench-top test stands will be developed to investigate radiation-induced effects in simulated environment. These include the effects of radiation on corrosion and corrosion control methods, spallation products (including polonium) on coolant chemistry and corrosion, corrosion products and activation, and mitigation and removal methods. These efforts will support future radiation campaigns in technology and test plan development, post-test analysis, and the development of reactor and/or spallation source driven test facilities.

Efforts will be initiated to perform screening tests of coolant compatibility for fuel cladding and fuels in candidate options. In collaborations with international R&D organizations in the development of ADS technologies and advanced reactors, we will investigate promising alloying and surface treatment techniques for enhanced corrosion resistance.

We will carry out option studies to support coolant technology selection and transmutation system designs. These include component selection and performance (e.g. electromagnetic vs mechanical pumps), forced circulation vs natural circulation, and lead vs lead-bismuth eutectic, acceptable temperature and flow conditions, coolant technology alternatives (e.g. oxygen controlled, surface treatment, and oxygen-free for high temperature and high performance systems).

This technology area is very amenable to international collaboration because there is a worldwide interest in using lead and lead-alloy technology as nuclear coolant for fast spectrum systems and as a target material for ADS systems. Internationally, many R&D organizations have coolant technology development programs and facilities. These activities will be incorporated into the planning, and the R&D tasks will be coordinated with international partners. In particular, we are participating in an OECD/NEA chartered LBE Expert Working Group to define the lead-alloys coolant technology performance envelop, and the DOE/JNC-JCC information exchange on lead-cooled reactor development.

**FY 2003 Plan** - A 1000-hour corrosion test using the DELTA Loop will be performed to systematically assess the performance of materials during the initial stage of oxide formation in the oxygen controlled lead alloy coolant. A small bypass of lead alloy flow will be constructed to extend the test temperature to the 600 to 650°C range, allowing assessment of corrosion resistance during transients, and determination of upper operating limits for existing materials and surface treatment. Initial testing of ultrasonic Doppler velocimetry adapted to high temperature lead alloy flows, and some online active corrosion probes based on electric impedance spectroscopy, will be performed.

The milestones for FY 2003 include:

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| • Complete DELTA loop conditioning                                   | 04/2003 |
| • Complete 1000-hour corrosion test                                  | 09/2003 |
| • Initiate lead alloy handbook                                       | 06/2003 |
| • Perform oxygen sensor calibrations with international participants | 09/2003 |

**Five-Year Plan** – Medium-to-long-term corrosion tests (over 6000 hours) will be planned and performed. Testing and analysis of specimens and piping in several strategic locations in the loop, with varying oxygen concentrations, will be performed to validate the system corrosion modeling. Erosion and possible liquid metal embrittlement will be studied. Component performance over time, under varying conditions, and lifetime limits will be tested. Heat transfer and thermal hydraulic tests for reactor (e.g., fuel assembly to coolant heat transfer) and spallation target designs will be planned and performed. Instrumentation, control systems and procedures, including flow, pressure, oxygen concentration and online corrosion measurement, will be developed, tested, and improved. In addition, radiation environment effects will be investigated, first in simulated environments with surrogate materials, then in integral irradiation campaigns. The development of the performance envelope is strongly tied to the technologies used for corrosion control (oxygen control, surface treated materials, etc.). Development of the necessary instrumentation (i.e., flow and pressure measurement) is part of the performance envelope development. It is important to note that there are significant lead-alloys related efforts in the U.S and the international Generation IV Programs for reactor applications. Close collaboration with those efforts is planned to advance the baseline technology. If necessary, the lead alloy in the DELTA Loop can be changed to pure lead for Generation IV Program materials screening and coolant technology assessment and development.

The major milestones for the next five years are summarized below:

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| • Complete DELTA loop conditioning.  | FY 2003 |
| • Complete 1000-hour corrosion test.   | FY 2003 |
| • Initiate lead alloy handbook.  | FY 2003 |
| • Perform oxygen sensor calibrations with international participants.                      | FY 2003 |
| • Complete analysis of 1000-hour test data.  | FY 2004 |
| • Determine baseline performance envelope based on data.                                   | FY 2004 |
| • Issue lead alloy handbook draft.   | FY 2004 |
| • Perform coolant technology option studies  | FY 2004 |
| • Initiate thermal hydraulics and heat transfer experiments                                | FY 2004 |
| • Initiate corrosion resistance enhancement efforts through alloying and surface treatment | FY 2004 |

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| • Complete first version of the coolant handbook including mostly data from experiments without irradiation.                            | FY 2005 |
| • Complete oxygen sensor development.   | FY 2005 |
| • Initiate compatibility screening of coolant, cladding and fuels   | FY2005  |
| • Initiate radiation environment effects studies (corrosion product activation and spallation products, including polonium and removal) | FY2005  |
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| • Complete 6000-hour corrosion test.  | FY 2006 |
| • Analyze test data from the 6000-hour test.  | FY 2006 |
| • Complete compatibility screening of coolant, cladding and fuels, recommend options  | FY 2006 |
| • Perform radiation environment effects studies   | FY2006  |
|   |         |
| • Complete natural circulation test.  | FY 2007 |
| • Issue second revision of the coolant handbook, including all the available irradiation effects data.                                  | FY 2007 |
| • Issue coolant performance envelope report.  | FY 2007 |
| • Recommend coolant technology, materials, and thermal hydraulic options  | FY 2007 |